PROGRAMMABLE ANODE APPARATUS AND ASSOCIATED METHOD

BACKGROUND OF THE DISCLOSURE

1. Field of the Invention

The invention relates to metal deposition on a substrate. More particularly, the invention relates to anodes used for metal deposition on a substrate.

2. Description of the Background Art

Sub-quarter micron, multi-level metallization is an important technology for the next generation of ultra large scale integration (ULSI) design. Reliable formation of interconnect features permits increased circuit density, improves the acceptance of ULSI, and improves the quality of individual processed substrates. As circuit densities increase, the widths of vias, contacts and other features, as well as the width of the dielectric materials between the features, decrease. However, the height of the dielectric layers remains substantially constant. Therefore, the aspect ratios for the features (*i.e.*, their height or depth divided by their width) increases. The increase in aspect ratios for such small interconnect features poses a challenge to traditional metal deposition processes. As a result, a great amount of ongoing effort is directed at the formation of void-free, nanometer-sized uniform ULSI features.

Electroplating, previously limited in integrated circuit design to the fabrication of lines on circuit boards, is now also used to deposit metals, such as copper, to form interconnect features (e.g., vias, trenches, and contacts). Metal electroplating can be performed by a variety of techniques. One embodiment of a feature fill process that utilizes electroplating of a semiconductor substrate (such as a wafer) involves initially depositing a diffusion barrier layer over the feature surfaces; depositing a conductive metal seed layer over the barrier layer using techniques such as physical vapor deposition (PVD) and chemical vapor deposition (CVD), and then depositing a conductive metal over the seed layer (that adheres to the seed layer) by electroplating. The deposited layer can be planarized by, for example, chemical mechanical polishing (CMP), to define a conductive interconnect feature. In this disclosure, the term "seed layer" is used interchangeably with the term "plating surface" to describe those external portions of a substrate where metal ions are deposited during electroplating. The term

"substrate" as used in this disclosure is intended to cover all wafers, substrates, or objects on which metal layers can be deposited.

Deposition of a metal in electroplating is accomplished by providing an electric current to the seed layer and then exposing the seed layer to an electrolytic solution containing the metal to be deposited. One embodiment of an electroplating system that performs such metal deposition is depicted in FIG. 1. The device, known as a fountain plater 10, deposits metal on the seed layer 15 of a substrate 48. The fountain plater 10 includes an electrolyte cell 12 having an upper opening 13, a removable substrate support 14, and an anode 16 mounted to and located near the base 447 of the electrolyte cell 12. A positive electrical pole 45 of the controller 42 is electrically coupled to the anode 16. A negative pole 43 of the controller 43 is electrically coupled to the seed layer 15 of the substrate via a plurality of contacts 256 disposed around the periphery of the electrolyte cell near the upper opening 13.

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The embodiment of contacts 256 depicted in FIG. 1 represents a simplified version in which the substrate does not rotate within the substrate support 14. Alternative embodiments of contacts (not shown) are integrated in the substrate support in a manner that permits the substrate to rotate within the electrolyte cell 12 while maintaining electric/current applied between the anode and the seed layer of the substrate. The electrolyte cell 12 comprises an anode base 90 and an upper container segment 92. The anode 16 is mounted to the anode base 90 by anode supports 94. A feed through 96 supplies electrical power to the anode and the electrical power is controlled by the controller 98. The upper container segment 92 is sealably fastened to anode base 90 by nuts and bolts, screws, or other suitable removable devices to permit the repair and/or replacement of the anode 16 or other components.

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The plurality of contacts 256 are configured to contact a plating surface 15 of the substrate that is immersed in an electrolyte solution contained in the electrolyte cell 12 to enable the deposition of metal on the substrate 48. The contacts 256 may take the form of a contact pin, a contact surface, or any known type of electrical contact. The contacts that are mounted about the periphery of the contact ring 20 are positioned to minimize irregularities of the electrical field applied to the seed layer formed on the plating surface 15 of substrate 48.

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A substrate support 14 is pivotably mounted above the upper opening and is displaceable between immersed and removed positions. When the substrate support 14

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is pivoted into the removed position, the attached substrate is removed upwardly from the electrolyte cell 12 through the upper opening 13. When the substrate support 14 is pivoted into the inserted position, the attached substrate is pivoted downward through the upper opening 13 such that the plating surface 15 of the substrate 48 is immersed in electrolyte solution contained in the electrolyte cell. While in the immersed position, metal ions (typically copper or a copper alloy) contained in the electrolyte contained in the electrolyte cell 12 may be deposited on the substrate. The substrate support 14 keeps the substrate connected to the substrate support when desired (for example using vacuum chucking, etc.).

A hydrophilic membrane 87 surrounds the anode 16. Alternatively, the hydrophilic membrane could be mounted to extend horizontally across the electrolyte cell 12 above the anode. The material of the hydrophilic membrane 87 is selected to filter anode sludge passing from the anode 16 into the electrolyte solution. Metal ions (i.e. copper) generated by the anode 16 are permitted to pass through the hydrophilic membrane 87 to the cathode 48. Electrolyte solution that is input from the input port 80 is directed around the anode. The electrolyte solution interacts with anode 16 causing anode (metal) ions to be released because of the electrolyte solution reacting with the anode. The electrolyte solution carries the metal ions generated by the anode 16 to the cathode 48.

During recirculation of electrolyte solution in the electrolyte cell 12, electrolyte solution is supplied to electrolyte cell 12 via electrolyte input port 80. The electrolyte solution in the electrolyte cell overflows an annular weir portion 82 formed on top of the electrolyte cell 12. The electrolyte solution that overflows the annular weir portion 82 drains into annular overflow drain element 83. The annular overflow drain element 83 discharges to the recirculation/refreshing element 89 via electrolyte output 88. The recirculation/refreshing element 89 reestablishes the chemical components of the electrolyte solution that is being supplied to the electrolyte input port to a prescribed electrolyte solution formulation. The use of refreshed electrolyte solution ensures that the metal deposition process is performed using electrolyte solution containing suitable percentages of metal ions. The refreshed electrolyte solution from the recirculation/refreshing element 89 is forced into the inlet port 80 to define a closed loop for the electrolyte solution. One embodiment of recirculating/refreshing element 89 for an electroplating system is disclosed in U.S. Patent Application No 09/289,074, filed

April 8, 1999, entitled "Electro-Chemical Deposition System" (incorporated herein by reference).

During the metal deposition process, a negative charge (applied from negative pole 43 of controller 42 via contacts 256 to a seed layer/plating surface 15 of substrate 48) causes the seed layer formed on the lower layer of the substrate to perform as a cathode that is electrically coupled to the anode 16 by the electrolyte solution 79. The seed layer attracts positive metal ions within the electrolyte solution 79, thus providing metal deposition.

A number of obstacles impair consistently uniform electroplating of copper onto substrates. One obstacle involves the positioning of the contacts. In the fountain plater 10 shown in FIG. 1, the contacts 256 are positioned to contact the periphery 102 of the seed layer, but not the center 104 of the seed layer on the substrate 48. The current density of the seed layer at the center 104 of the substrate 48 will therefore be lower than the current density of the seed layer at the periphery 102 of the substrate 48 as a result of the relative distances from the contacts 256 to the respective center 104 and periphery 102 of the substrate. Current delivered from a portion of the anode to the cathode seeks out the lowest resistance path to the cathode. Due to irregularities of the electric current densities of the seed layer caused largely because of the positioning of the contacts 256 to the plating surface of the substrate, the deposition rates across the substrate may vary.

Anodes are designed to apply a uniform electric field (taken in a horizontal plane) in the electrolyte solution contained in the electrolyte cell 12. The contacts 256 contact the seed layer on the substrate adjacent the periphery of the seed layer. The current density at the center of the seed layer on the substrate is less than the current density of the seed layer at the periphery of the substrate due to the resistance of the material of the seed layer.

Therefore, a need exists in the art for an anode to be configured to partially compensate for irregularities in the current density generated across the seed layer on the substrate. Providing a uniform current density across the seed layer on the substrate from the periphery to the center provides a uniform and predictable deposition of electroplated material across the seed layer on the substrate.

SUMMARY OF THE INVENTION

The invention relates generally to anodes. In one aspect, a programmable anode is used in a metal deposition system containing a cathode. The anode includes a plurality of distinct anode segments and an electrical source. The electrical source is coupled to each of the anode segments.

BRIEF DESCRIPTION OF THE DRAWINGS

The teachings of the present invention can be readily understood by considering the following detailed description in conjunction with the accompanying drawings, in which:

FIG. 1 shows a cross sectional view of a prior art embodiment of fountain plater;

FIG. 2 shows a cross sectional view of one embodiment of fountain plater of the present invention;

FIG. 3 shows one embodiment of method to be performed by the controller shown in FIG. 2;

FIG. 4 shows an alternate embodiment of method to be performed by the controller shown in FIG. 2;

FIG. 5 shows a view as taken through sectional lines 5-5 of FIG. 2;

FIG. 6 shows a view similar to FIG. 5 of an anode having a rectangular configuration;

FIG. 7 shows a top view of another embodiment of programmable anode; and

FIG. 8 is one embodiment of a graph plotting gradient current density value as a function of the position on the substrate.

To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures.

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DETAILED DESCRIPTION

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After considering the following description, those skilled in the art will clearly realize that the teachings of this invention can be readily utilized in metal ion deposition applications, and more particularly to configure and provide anodes that can be selectively energized. In at least one aspect, programmable anode is provided that improves the uniformity of the current density applied across a seed layer on a substrate (e.g.,wafer).

In this disclosure, the terms "metal" and "metal ions" are used to describe those ions, particles, and pieces made including copper and other metals that can be transported to a cathode to be deposited upon the cathode under the influence of an electrical charge established between the anode and the cathode.

A. Electroplating Cell Configuration

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FIG. 2 is a cross sectional view of a fountain plater 10 having an electroplating cell 200 according to one embodiment of the invention. The electroplating cell 200 comprises the programmable anode 201. The programmable anode 201 is configured to provide for independent control of the electric current passing through certain segments of the anode. The control of individual currents passing through respective individual segments of the anode provides variation of the electric field in the electrolyte solution contained in the electrolyte cell that can modify the metal deposition uniformity/non-uniformity across the substrate.

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In the embodiment shown in FIG. 2, the anode 201 comprises a plurality of anode segments 203a, 203b, 203c, and 203d, with each one of the anode segments formed from such materials as a high purity, oxygen free, copper (Cu). Each one of the plurality of anode segments 203a, 203b, 203c, and 203d are geometrically centered about an imaginary segment axis 208, and each anode segment has respective substantially coplanar upper segment surfaces 205a, 205b, 205c, and 205d. While four anode segments 203a, 203b, 203c, and 203d are shown in FIG. 2, any suitable number may be provided. Additionally, each one of the plurality of anode segments 203a, 203b, 203c, and 203d have respective lower substantially coplanar segment surfaces 207a, 207b, 207c, and 207d. Insulating connecting members 210 connect adjacent ones of the plurality of anode segments 207a, 207b, 207c, and 207d. The anode 201 typically comprises a hydrophilic membrane 97 as shown in the embodiment shown in FIG. 1 and described above, but is not depicted in FIG. 2 for simplicity of display.

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The anode 201 is configured as a modular assembly that provides for secure positioning and relatively easy replacement of the assembly and the anode segments. Insulating base support 270 extends between, and is connected to, the anode base 90 and at least one anode segment of the anode 201. Replaceable fasteners such as nuts, bolts, etc. can be used to connect the insulating base support 270 to the anode base 90 and the insulating base support 270 to at least one of the anode segment 203a, 203b, 203c, or

203d. Insulative support members 210 physically support each anode segment 203a,

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203b, 203c, and 203d relative to an adjacent anode segment (as shown in FIG. 5). The insulative support member 210 is formed of an insulative material that limits electric current passing between adjacent anode segments 203a, 203b, 203c, and 203d, such that each anode segment can be individually electrically biased to a separate potential. The insulative base support 270 and the insulative support members 210 interact to maintain each of the anode segments 203a, 203b, 203c, and 203d fixed in position relative to the anode base 90 and the remainder of the electrolyte cell 201 during operation, while keeping each one of the anode segments 203a, 203b, 203c, and 203d relatively insulated from one another and from the cell wall.

Portions of the anodes 201 are consumed by the electroplating process, resulting

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in the production of anode sludge. Portions of the anode being consumed results in the anode assuming an irregular shape and contour. For example, the height of a worn anode is often inconsistent. Therefore, regular anode replacement is necessary to maintain uniform electric field generation within the electrolyte cell. When the anode 201 does become irregularly shaped due to portions of the anode being consumed, or for other reasons, the anode 201 should be replaced. To replace the anode, the upper container segment 92 is removed by lifting the upper container segment from the anode mount 90 after removing the fasteners that connect these two elements. The anode 201 is then disconnected from the anode base 90, and the anode 201 is removed as a modular unit. A replacement modular anode 201 is then inserted and connected to the anode base 90. The upper container segment is then repositioned and fastened to the anode base, and will appear in the assembled position as shown in FIG. 2. In another embodiment, the anode 201 and the anode base 90 can be provided as a single modular unit. In this latter embodiment, another modular anode 201/anode base 90 unit is provided to replace the anode base 90 connected to the consumed anode 201. The upper container segment is then repositioned and fastened to the anode base in the position shown in FIG. 2.

Each one of the plurality of anode segments 203a, 203b, 203c, and 203d are

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electrically connected to the controller 254 by respective electrical contacts or feed-throughs 206a, 206b, 206c, and 206d that extend through the electrolyte cell 12 (preferably through the base 447 of the electrolyte cell 12). The feed-throughs 206a, 206b, 206c, and 206d are individually insulated by a coating such as an elastomeric or insulative plastic. The coating limits direct chemical or electrical reaction with the

~~electrolyte solution, and especially those portions that extend within the electrolyte cell 200. Anode support members 270 rigidly and insulatively support at least one anode segment 203a, 203b, 203c, and 203d relative to the base 447 of the electrolyte cell 220. Although the anode segments 203a, 203b, 203c, and 203d are depicted as being cylindrical or ring-shaped, any suitable anode configuration may be utilized where the anode is segmented into a plurality of anode segments 203a, 203b, 203c, and 203d. For example, the anode segments may be rectangular as depicted in FIG. 6 and described below.~~

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A controller 254 shown in the embodiment of FIG. 2 controls electric voltage or current supplied to each anode segment 203a, 203b, 203c, and 203d. The controller 254 comprises central processing unit (CPU) 260, memory 262, circuit portion 265, input output interface (I/O) 264, and bus 266. The controller 254 may be a general-purpose computer, a microprocessor, a microcontroller, or any other known suitable type of computer or controller. The CPU 260 performs the processing and computations for the controller 254, and controls the operation of the anode 201 by applying a controllable electrical voltage to each distinct anode segment 203a, 203b, 203c, and 203d.

The memory 262 includes random access memory (RAM) and/or read only memory (ROM) that together store the computer programs, operands, operators, dimensional values, system processing temperatures and configurations, and other parameters that control the electroplating operation. A bus (not shown) provides for digital information transmissions between CPU 260, circuit portion 265, memory 262, and I/O 264, and also connects I/O 264 to the portions of the fountain plater 10 and the associated equipment that either receive digital information from, or transmit digital information to, controller 254.

I/O 264 provides an interface to control the transmissions of digital information between each of the components in controller 254. I/O 264 also provides an interface between the components of the controller 254 and different portions of the fountain plater 10. Circuit portion 265 comprises all of the other user interface devices (such as display and keyboard), system devices, and other accessories associated with the controller 254. While one embodiment of digital controller 254 is described herein, other digital controllers as well as analog controllers could be applied to this application, and are within the intended scope of the invention.

The embodiment of anode 201 shown in FIG. 2 produces an electrical field whose shape can be controllably adjusted. The controllable electrical field produced by the programmable anode 201 results in generation of a controllable electric current density across the seed layer on the substrate. The controller 254 controls the shape of the electromagnetic field generated by the combined effects of the plurality of the individual anode segments 203a, 203b, 203c, and 203d by controlling the electric current supplied to each individual anode segment 203a, 203b, 203c, and 203d.

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The electric field generated by anode segments 203a, 203b, 203c, and 203d are depicted respectively as electric flux lines 209a, 209b, 209c, and 209d. The electric flux lines are shown only for the right side of the electrolyte cell 12 for display simplicity. The electric flux lines on the right side are a mirror image of the electric flux lines shown on the right side, and are not shown. Some metal ions will vary from directly following the electric flux lines due to fluid flow currents existing in the electrolyte solution, diffusion of the metal ions transverse to the electric flux lines, and other such factors. The electric flux lines 209a, 209b, 209c, and 209d represent the general direction that metal ions that are generated by the respective anode segments 203a, 203b, 203c, and 203d follow as the metal ions travel to the cathode 48. For those anode segments 203d that generate the electric flux line 209d that extends outside the periphery of the plating surface, the metal ions primarily flow around the outside periphery of the plating surface.

The electric flux lines 209a, 209b, and 209c also represent the general direction of the electric current from anode segments 203a, 203b, and 203c to the cathode (electric flux line 209d passes outside of the periphery of the substrate). The electric flux lines 209a, 209b, 209c, and 209d typically extend from a respective anode segment 203a, 203b, 203c, and 203d to the portion of the cathode (substrate 48) that is nearest to the anode segment since the current delivered from any anode segment to the cathode seeks out the shortest (e.g., lowest resistance) path to the cathode. For example, electric flux line 209a is directed from anode segment 203a, and intersects the plating face 15 of the substrate 48 substantially perpendicularly that represents the shortest distance from the anode segment 203a to the substrate 48.

The metal ions are dissociated from within a volume of the electrolyte solution (including e.g. copper sulfate) into positively charged copper ions and negatively charged sulfate ions. The copper ions in the region of the substrate/cathode are attracted

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to the seed layer on the substrate. The excess of sulfate ions remaining in the electrolyte solution contributes to the formation of a depletion region 270 adjacent to the distinct anode segments 203a, 203b, 203c, and 203d. The dissociated metal ions are deposited on the seed layer on the substrate 48. Increasing the electrolyte solution flow from the input port 80 (and the corresponding electrolyte solution output flow over the annular weir portion 82) provides for decreasing the physical size of the depletion region 270 by replacing the depleted components. This replacing the depleted components increases the supply of copper sulfite in the electrolyte solution adjacent the seed layer. The process of dissociating metal ions from the copper sulfite continues where the dissociated metal ions may be deposited on the seed layer.

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A reference sensor 250 is shown positioned in close proximity, but spaced from, a substrate 48 positioned for a plating operation (for example, in the contact ring 230). The reference sensor 250 monitors surface potential (current density) at the plating surface 15 of the substrate 48. The reference sensor 250 is positioned as far as possible from any contact 256 supplying current/voltage to the substrate. This physical isolation of the reference sensor 250 from contacts 256 limit the electrical effects resulting from a contact that is proximally located to the reference sensor. The electric current density in the seed layer on the substrate is partially determined by an electric field generated in the electrolyte solution contained in the electrolyte cell 12. When the other electrolyte solution properties are held constant, the electric field and the current density generated in the electrolyte solution is controlled by several factors including controlling the electric current flowing through the different ones of the individual anode segments 203a, 203b, 203c and 203d of the anode 201 as well as changing the shape and configuration of the anode. Therefore, the surface potential monitored adjacent the surface of the substrate by the reference sensor 250 provides an indication of the effect of the current flowing in the individual anode segments 203a, 203b, 203c, and 203d of the anode 201.

Only one reference sensor is depicted in the embodiment shown in FIG. 2. However, a plurality of reference sensors 250 are provided at various locations within the electrolyte cell 12 to provide a more accurate indication of the surface potential such as current density from the periphery to the center of the seed layer on the substrate. The reference sensors 250 are preferably spaced from each other, and the reference sensors are each positioned adjacent various surface locations across the plating surface

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of the substrate 48. One or more frameworks (not shown) formed from a material that is non-reactive with the electrolyte solution may be provided within the electrolyte cell to support the reference sensor(s) 250 in a desired position.

In an alternate embodiment (not shown), a dummy wafer made of a non-reactive material has an array of sensors 250, the array is preferably arranged in dummy wafer locations corresponding to the actual locations on the seed layer of the substrate that readings provide useful information. Readings may be desired about the periphery of the seed layer on the substrate, in the center of the seed layer on the substrate, and at various locations across the seed layer on the substrate. Each sensor located in the dummy wafer extends from, and senses, the current density in the electrolyte solution in close proximity to the lower surface of the dummy wafer. The dummy wafer can then be inserted into the electrolyte cell 12 in a position similar to where the substrate 48 is positioned in the embodiment shown in FIG. 2. Since the sensors are located on the dummy wafer at a location that corresponds to the respective location to be sensed on the actual substrate, process conditions (current density, etc.) can be applied to the dummy wafer. The outputs of the reference sensors provide an indication of the current density values experienced on the seed layer on a substrate under similar process conditions as one or more of the plurality of anode segments 203a, 203b, 203c, and 203d are energized.

While the embodiment of programmable anode shown in FIG. 5 includes a plurality of generally cylindrical anode segments 203a, 203b, 203c, and 203d, the anode segments in programmable anodes can be arranged in a variety of anode shapes. For example, another embodiment of a programmable anode 600 shown in FIG. 6 comprises a plurality of rectangular anode segments 602a, 602b, 602c, and 602d. The programmable anode 600 is configured to process a generally rectangular substrate such as a LCD display. The concepts of operation of the programmable anodes that are described above relative to the embodiment shown in FIG. 5 also apply generally to the embodiment shown in FIG. 6. Programmable anode having multiple anode segments described herein can be applied to a variety of substrate and anode shapes and configurations.

FIG. 7 discloses an alternate embodiment of a programmable anode 700 comprising a plurality of anode segments 702a, 702b. The anode segments 702a and 702b are not arranged about a single axis as with the anode segments 203a, 203b, 203c,

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and 203d in the embodiment shown in FIG. 2. Anode segment 702a is oriented about axis 704a while anode segment 702b is oriented about axis 704b. Axis 704a is offset from axis 704b. This displacement of the anode segments from each other compensates for non-uniformities in the current density of the seed layer. Assume during processing, one side of the horizontal surface of the seed layer on the substrate is coated more heavily than the other side of the horizontal surface of the seed layer. In one embodiment of the programmable anode 700, anode segments 702a is fixed relative to anode segment 702b shown in the embodiment of FIG. 7. The offset of axis 704a from axis 704b compensates for a heavier current density at one side of the periphery of the seed layer than the current density at the other side of the periphery of the seed layer. It is envisioned that similar irregularities in multiple anode segment spacing may be provided to compensate for irregularities in the current density across the seed layer on the substrate. Additionally, irregularities of the size and shape of any single anode segment may be used to compensate for irregularities in the current density across the seed layer on the substrate.

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The anode segment 702a can be shifted horizontally to the anode segment 702b in an alternate embodiment of programmable anode, still referring to FIG. 7. Assume that it is determined by the reference sensor 250 that the current density is not at the same level across the seed layer on a substrate during processing. One anode segment 702a or 702b is shifted to make the current density in the seed layer uniform. The relative positions of the axis 704a and 704b of the anode segment 702a or 702b can be adjusted by loosening a clamping mechanism (not shown) that secures either or both of the anode segments 702a, 702b relatively in position. Anode segment(s) 702a or 702b as then repositioned as desired. Following repositioning of the anode segments, the clamping mechanism is reclamped to maintain the anode segments 702a and 702b in position. Additionally, the thickness of certain portions of the anode segments can be altered as shown by arrows 706a and 706b to alter the current density applied to specific locations of the seed layer on the substrate as desired.

B. Variable Anode Timing Actuation Embodiments

FIGs. 3 and 4 show flow charts of two embodiments of methods performed by the controller 254 in controlling electricity applied to the anode 201. These methods are illustrative in nature, and are not intended to be limiting in scope of the type of methods

that can be performed by the controller. The method of FIG. 3 energizes an inner anode segment 203a then temporally sequentially energizes progressively outwardly positioned anode segments 203b, 203c, and 203d. In this method, there is a typically a wait period between the activation of each successive anode segment. This method results in each inner anode segments being energized for a longer duration than each successive outer anode segment. To compensate for irregularities across the face of the seed layer, the anode segments do not have to be energized or de-energized in order. For example, one inner anode segment does not have to be energized prior to the next adjacent anode segment. Also, it is not necessary that all anode segments be de-energized concurrently. For example, all anode segments can be energized at the same time, and the outer anode segments are de-energized first.

The embodiment of metal ion deposition shown in FIG. 3 overcomes a non-uniform metal deposition situation, as described above, in which contacts positioned around a periphery 102 of a substrate supply electricity to the substrate. Such non-uniformity in location of contact by the contacts 256 result in a non-uniform current density, as considered from the edge to the center of the seed layer on the substrate. This non-uniform current density across the face of the seed layer on the substrate results because the contacts are positioned closer to the periphery 102 of the substrate than the center 104 of the substrate. The resistance of the seed layer on the substrate limits some of the electrical current supplied by contact from passing from the periphery of the seed layer to the center of the seed layer. This resistance of electrical current passing from the periphery of the seed layer to the center of the seed layer diminishes the level current density of the seed layer near the center of the seed layer relative to the current density and the surface potential near the periphery of the seed layer.

Electric current from each anode segment seeks to travel to the seed layer portion that is nearest to that anode segment. Therefore, a portion of the seed layer closer to a particular anode segment receives a higher current density from that particular anode segment since current delivered from an anode to a cathode seeks out the shortest path. The reason that current from each anode segment seeks to travel to the nearest cathode location is that less resistance is necessary to travel the shortest distance through a homogenous electrolyte solution to the nearest seed layer location.

An instantaneous gradient current density value is established across the seed layer for each seed layer location. One embodiment of instantaneous current density graph 800 is shown in FIG. 8 where the abscissa 802 represents position from the center (left) to the periphery (right) in a semiconductor wafer and the ordinate 804 represents gradient current density value (in arbitrary units). The instantaneous gradient current density value represents a product of current density multiplied by the time that the seed layer location is at a specific current density. The rate of metal deposition on the seed layer is proportional to the instantaneous gradient current density value.

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The instantaneous gradient current density value is a function of the voltage/current in each anode segments as well as the voltage/current in the contacts 256. For example, gradient current density value 806a represents when only the inner anode segment 203a shown in FIG. 2 is energized. Gradient current density value 806b represents when only anode segments 203a and 203b are energized. Gradient current density value 806c represents when only anode segments 203a, 203b, and 203c are energized. Gradient current density value 806d represents when all of the anode segments 203a, 203b, 203c, and 203d are energized. As shown in FIG. 8, as different combinations of the anode segments 203a, 203b, 203c, and 203d are energized, the instantaneous gradient current density value will vary. The gradient current density values 806a, 806b, 806c, and 806d shown in FIG. 8 are exemplary in nature, and are provided on a dimensionless scale. The total gradient current density value 808 represents the sum of the instantaneous gradient current density values 806a, 806b, 806c, and 806d for each seed layer location during the period that metal ions are being deposited across the substrate. The total gradient current density values should be substantially constant from the periphery to the center of the seed layer to ensure a uniform depth of metal deposition across the seed layer on the substrate.

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The controller 254 can alter the duration and/or current level applied from each anode segment (thereby varying the instantaneous gradient current density value) to compensate for the non-uniform current density existing across the face of the seed layer. The non-uniformities exist because the contacts are positioned closer to the periphery 102 of the substrate than the center 104 of the substrate as described above. Controlling the electric current applied from the combined anode segments 203a, 203b, 203c, and 203d across the width of the programmable anode 201 compensates to provide a uniform current density across the seed layer. By controlling the electric

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current applied through the individual anode segments 203a, 203b, 203c, and 203d, the current density near the center 104 of the seed layer on the substrate can be adjusted relative to the current density near the periphery 102 of the seed layer on the substrate.

FIG. 5 shows vertically oriented spaces, shown by arrows 502, being formed between adjacent coplanar upper segment surfaces 205a, 205b, 205c, and 205d. Electrolyte solution can pass through spaces when passing from below the anode to above the anode. The widths of the spaces are minimized to increase those areas of the anode that have an upper surface that are capable of generating metal ions. Minimizing the width of the spaces therefore enhances the uniformity of the production of metal ions into the electrolyte solution across the width of the electrolyte cell 12 by the combined anode segments. The widths of the anode spaces 502 are sufficient to isolate the adjacent anode segments 203a, 203b, 203c, and 203d.

Two embodiments are now described that compensate for current density being higher at the periphery of the seed layer than at the center of the seed layer. In a first embodiment, only inner anode segments 203a or 203b are energized for a longer total duration than the outer anode segments 203c or 203d are energized.

In a second embodiment, the current/voltage level applied to the different anode segments 203a, 203b, 203c, and 203d are varied based upon sensed current density. A suitable increase/decrease of the current/voltage applied between the different anode segments 203a, 203b, 203c, and 203d thus makes the electrical current density across the seed layer on the substrate from the periphery to the center uniform. Therefore, the instantaneous gradient current density value is made uniform from the center of the seed layer to the periphery of the seed layer.

FIG. 3 shows a method of performing an embodiment of equalizing non-uniform current densities from the periphery to the center of the substrate, in which the periods during which a current or voltage being applied to the different anode segments 203a, 203b, 203c, and 203d are individually controlled to control the current density in a selected portion of the seed layer. The method shown in FIG. 3 starts at step 302 by an operator or a robot (not shown) inserting a substrate 48 to be electroplated into the substrate support 14. After the substrate has been inserted into the substrate support 14, the substrate 48 is located within the electroplating cell 200 in the position as depicted in the embodiment shown in FIG. 2.

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The method 300 then continues to step 304 in which the controller 254 applies electric voltage/current at a prescribed level to actuate the inner anode segment 203a. The method 300 then continues to step 306 where the controller 254 waits for a prescribed duration during which time the electric voltage/current applied during step 304 continues to be applied to only the inner anode segment 203a. The application of electric voltage or current to the inner anode segment 203a is maintained until step 313. When only inner anode segment 203a (and not anode segments 203b, 203c, and 203d) is actuated, a higher current density is applied to the center 104 of the seed layer on the substrate 48 than to the periphery 102 of the seed layer on the substrate 48. Energizing inner anode segment 203a results in the current density being higher near the center of the seed layer compared to the side of the seed layer. This higher current density results because the inner anode segment 203a is physically located closer to the center 104 of the seed layer on the substrate 48 than the periphery 102. Electrical resistance from any anode segment to the nearest seed layer is lower than the resistance to other portions of the seed layer, as described above. During the period that only the inner anode segment 203a is actuated, the rate of metal ion deposition performed within the electroplating cell 12 is higher near to the center 104 of the seed layer 15 of the substrate 48 than near the periphery 102 of the seed layer.

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The method 300 continues at steps 308 and 310 by sequentially applying current/voltage to the next anode segment 203b. After the subsequent inner anode segment 203b is actuated, then the controller 254 continues in step 310 by maintaining the current/voltage levels to both anode segments 203a and 203b that have been actuated. In step 310, for example, a higher current density exists at the periphery of the seed layer on the substrate 48 than in step 304 because both anode segments 203a and 203b are actuated, and anode segment 203b is closer to the periphery of the seed layer then the anode segment 203a. Anode segment 203b is closer to the periphery of the seed layer 15 than anode segment 203a. Therefore, metal ions will be deposited in step 310 to form a deposited metal layer at a heavier rate near the periphery 104 of the plating surface in step 310 than in step 304.

The electric current/voltage being supplied to both anode segments 203a and 203b is maintained until step 313. In step 312, electrical voltage and current is applied and maintained to each subsequent outer anode segment 203c and 203d in a manner similar to that described above relative to the inner anode segments 203a and 203b.

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Once electric current is provided to each one of the specific anode segment 203a, 203b, 203c, or 203d, current is maintained in the anode segment until step 313. Since the inner anode segments (203a, then 203b, then 203c) are energized first, the duration that electrical voltage/current is applied to the inner anode segments is longer than the duration that electrical voltage/current is applied to the outer anode segments. Following the actuation of each subsequent anode segment 203a, then 203b, then 203c, then finally 203d (that represents the order of actuation of the anode segments), the substrate experiences a higher current density adjacent the periphery 102 of the seed layer on the substrate relative to the center 104 of the seed layer on the substrate than prior to the actuation of that particular anode segment.

The current density near the periphery 102 of the seed layer on the substrate is higher after outer anode segments are energized since the outer anode segments 203c and 203d are physically located nearer the periphery of the substrate than the inner anode segments 203a and 203b. Current delivered from a portion of an anode to a portion of an anode seeks out the closest path. A lower electrical resistance exists through the electrolyte solution from the outer anode segments 203c and 203d than the inner anode segments 203a and 203b to the periphery of the substrate. Additionally, a lower electrical resistance exists through the electrolyte solution from the outer anode segments 203c and 203d than the inner anode segments 203a and 203b to the periphery of the substrate. Thus, following actuation of each subsequent anode segment 203a, 203b, 203c, and 203d, a higher relative metal deposition rate occurs nearer the periphery 102 of the seed layer.

Since the actuation of each successive outward anode segment 203b, 203c, and 203d results in more metal being deposited near the periphery, the deposition thickness of metal ions across the face of the substrate can be controlled by regulating the duration that electrical voltage/current is applied to each anode segment 203a, 203b, 203c, and 203d . The duration at which each anode segment 203a, 203b, 203c, and 203d is maintained in each one of steps 306, 310, and 312 should be determined empirically upon consideration of the gradient current density valves and the associated deposition rate at the periphery 102 of the seed layer on the substrate 48 compared to the center104 of the seed layer on the substrate after each successive anode segment 203a, 203b, 203c and 203d is energized.

The contact 256 being positioned adjacent the periphery of the plating surface 15 of the substrate 48 increases the current density at the periphery of the seed layer compared to at the center of the seed layer, as described above. The timing of the energizing of the individual anode segments 203a, 203b, 203c, and 203d is controlled by the controller 254 as described below to increase the current density near the center of the seed layer. This increase in current density near the center of the seed layer compensates for the increased voltage in the seed layer near the periphery.

The plurality of reference sensors or current density sensors 250 are positioned across (and adjacent to) the plating surface across the width of the substrate quantitatively indicates the current density at certain locations of the seed layer. A quantitative indication of the current density at certain locations of the seed layer when certain ones of the anode segments 203a, 203b, 203c, and 203d are energized can be derived from reference sensors 250. The voltage levels applied to certain suitable anode segment 203a, 203b, 203c, and 203d can be changed to equalize the current density value across the substrate. From these quantitative indications of the current density levels at different seed level location, a skilled operator can empirically determine the timing of the actuation of each anode segment. Such empirical determination of the timing of the actuation of the anode segments 203a, 203b, 203c and 203d is preferred since the use of different electroplating cells having different substrate and/or anode configurations make a precise determination of current density in the distinct seed layer locations of the seed layer on the substrate based upon mathematical calculations difficult.

The controller 254 applies waiting periods during steps 306, 310, and 312 based upon input from the operator or the sensor indicating the current density (preferably by inputs from operators after empirical considerations) to provide a metal ion deposition layer having the desired thickness across the seed layer 15 of the substrate 48 following the completion of each application of method 300. For instance, if after completing one application of method 300, the depth of the deposited layer adjacent the periphery of the substrate 102 is greater than the depth of the deposited layer at the center 104 of the substrate, then the wait period at step 306 and/or 310 can be suitably increased. If the depth of the deposited layer adjacent the periphery of the substrate 102 after completing one application of method 300 is less than the depth of the deposited layer at the center 104 of the substrate, then the wait period at step 306 and 310 can be suitably decreased. After several substrates 48 are electroplated under the influence of

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controller 254, the depth of the deposited material across the plating surface of these subsequent substrates can be precisely measured. The wait periods between energizing such subsequent anode segments 203a, 203b, 203c, and 203d can be modified to compensate for any non-uniformities in depth of the deposited material across the plating surface 15 of the substrate 48.

Alternatively, the controller 254 as described above can derive the timing of the actuation of the different anode segments 203a, 203b, 203c, and 203d based upon the determined current density at different locations of the seed layer (the gradient current density valve) as determined by the current density sensors. The controller 254 would preferably use a best-fit program in determining the timing of the actuation of the different anode segments to provide a uniform metal ion deposition depth from the periphery to the center of the substrate that results in a desired total gradient current density valve.

The substrate 48 is then removed from the electroplating cell in step 312. The method 300 then continues to step 316, in which the controller 254 determines whether any subsequent substrates 48 are to be inserted into the electroplating cell for further electroplating. If there are any subsequent substrates 48, then the method 300 repeats itself by looping back to step 302. If there are no other subsequent substrates, then method 300 terminates. Method 300 may be repeated or reaccessed (using similar loops) in case further substrates are to be processed by the electroplating cell 200.

The FIG. 3 method described above provides a controller 254 that controls the total duration that each anode segment is energized by controlling the initial time that each anode segment begins to be energized. However, there are other methods by which duration of each one of the different anode segments can be controlled. For instance, each anode segment can be energized successively for its total desired duration. That is, anode segment 203a can be energized for a desired number of seconds and then de-energized, then anode segment 203b can be energized for a desired number of seconds and then de-energized, and the same for anode segments 203c and 203d. In another embodiment, all anode segments can be energized concurrently, and the total duration that each individual anode segment is energized is controlled by the controller 254 by controlling the de-energizing time that each anode segment is de-energized. That is, all anode segments 203a, 203b, 203c, and 203d are all energized concurrently, and then anode segment 203d is de-energized following the desired duration. Anode segments

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203a, 203b, and 203c are then maintained for a desired period representing the difference is true that anode segment 203d is to be actuated compared to anode segment 203c. Anode segment 203c is then de-energized. The same process of de-energizing applies to anode segment 203b and finally 203a following their respective periods.

C. Variable Currents between Anode Segments

FIG. 4 shows another embodiment of a method 400 controlled by the controller 254 that can be used to control the electroplating process within the electroplating cell 200. The method 400 shown in FIG. 4 continually balances the electric current density (and surface potential) applied across the seed layer on the substrate 48. The electric current density values of the seed layer on the substrate are monitored by the controller 254 upon sensing one or more reference sensors 250. The reference sensors can be either mounted in the electrolyte cell or chamber 12, in a connecting member across the electrolyte cell (not shown), or in a dummy wafer occasionally inserted into the electrolyte cell to measure the current density as described above. While one reference sensor 250 is depicted in the embodiment of FIG. 2, any reasonable number of reference sensors may be used.

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The reference sensors 250 may be any of the variety of sensors that can sense current density on the seed layer on the substrate, as described above. Since the controller 254 in this embodiment considers surface potential across the substrate, if only one reference sensor is used, then the surface potential at different locations have to be assumed. Such assumptions can result from an empirical knowledge of the electroplating process, or quantitative measurements at certain locations within the electroplating cell 12 assuming that the measured values do not change. Any variation in monitored electric current values on the substrate 48, as sensed by the reference sensors 250 described above, is fed into the controller 254. The controller 254 alters the electric current applied to the anode segments 203a, 203b, 203c, and 203d to control the electric current density applied across the seed layer on the substrate. The embodiment in FIG. 4 is directed at controlling the voltage/current applied to the distinct anode segments 203a, 203b, 203c, and 203d making the sensed current density across the seed layer on the substrate substantially uniform. It is also possible to combine the teachings of the FIG. 4 embodiment with the teachings of the FIG. 3 embodiment, and thus regulating the duration that each anode segment is energized.

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The method 400 begins with step 402 in which a substrate to be electroplated is inserted into the electroplating cell 200. The method 400 continues to step 404 in which the controller 254 applies electricity to each one of the plurality of anode segments 203a, 203b, 203c, 203d (See FIG. 2). During step 404, the current/voltage levels applied to each one of the plurality of anode segments is initially preferably at a single voltage level. Thus, the electric field generated by the anode 201 to the substrate 48 should be substantially uniform in the electrolyte solution across the width of the process chamber 223 in the electrolyte solution (such uniformity excludes boundary conditions adjacent the walls).

The anode producing a uniform electric field across the diameter of the substrate is to be considered in combination with non-uniform electric current density and surface potential existing across the seed layer of the substrate due to the irregularities in current densities applied by the contact 256 that contact the periphery of the substrate 48, as described above. Therefore, the uniform electric field produced by the anode is to be altered to compensate for non-uniformities in the current density in the seed layer across the substrate. The above reference sensors 250 provide an indication of the electric field generated within the cell layer adjacent the substrate-cathode 48. This sensing of irregularities of the current density is preferably accomplished by an array of reference sensors 250 that are positioned to extend across the substrate 48. Any unevenness in the current density in the seed layer may provide an uneven deposition layer across the substrate.

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Method 400 continues to step 406 in which the controller 254 senses the irregularities in electric field applied to the cathode from the anode, and the resultant surface potential on the surface of the substrate 48. A dummy substrate may be provided having sensors embedded therein such that the dummy substrate is inserted in the electroplating cell in a manner similar to an actual substrate. The anode 201 is then energized, along with electric fields applied to contact points 256. Method 400 continues to step 408 in which the controller 254, based on sensed non-uniformities in the electromagnetic field to the cathode, determines whether to adjust the electric field applied to any one of the anode segments 203a, 203b, 203c, or 203d to modify the current density across the seed layer on the substrate.

A higher current density is applied from each anode segment to a closer seed layer location because the resistance to electrical current flow from the anode segment to

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the nearest portion of the seed layer is lower than the resistance to other, further separated, portions of the seed layer. If the reference sensors determine that the electric field sensed by the reference sensor 250 located adjacent the periphery 102 of the substrate 48 is stronger than the electric field applied to the center 104 of the substrate 48, then only those anode segments located closest to the center of the substrate 48 (such as 203a and perhaps 203b) should have their current/voltage levels increased. Alternatively, only those anode segments located closest to the periphery of the seed layer 48 should have their current/voltage levels decreased. Though the above describes controlling the electric voltage/current levels to the anode segments 203a, 203b, 203c, and 203d to compensate for a relatively simple non-uniformity (the periphery of the seed layer has a stronger current density than the center of the seed layer), it is intended that the controller 254 (or a skilled operator) can alter the electricity applied to the individual anode segments to make a more complex non-uniformity substantially uniform. The controller 254 continues to step 410 in which the current applied to each distinct anode segment 203a, 203b, 203c, 203d is then adjusted to compensate for such irregularities.

Even after the controller 254 adjusts distinct anode segments to equalize current across the plating surface 15 of the substrate in step 410, there still might be some unevenness of electric field applied to the substrate. For this reason, the method continues to decision step 411 in which the controller 254 again measures the surface potential adjacent the plating surface 15 of the substrate 48 to determine whether all of the sensed irregularities in the electric fields (e.g. current density) that were sensed in step 408 and adjusted in step 410 have been corrected by the adjustment.

If the answer to the decision step 411 is no, then the method continues back to step 406 in which the irregularities in the electric field applied to the cathode (as indicated by the current density in the substrate) from the anode are once again adjusted in an attempt to make the current density across the seed layer on the substrate more uniform. More adjustment to the electricity applied to different ones of the anode segments 203a, 203b, 203c, and 203d is therefore necessary. The duration that the controller 254 requires for each loop of steps 406, 408, 410, and decision step 411 is relatively brief (considering the speed of modern processor) compared to the time that metal is being deposited in the electroplating process. Therefore, a relatively brief time is required to adjust the electricity within the anode segments 203a, 203b, 203c, and

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203d to provide substantially uniform metal deposition. Steps 406, 408, 410, and decision step 411 therefore form a loop which is continued until the controller 254 determines that the electric field as sensed by the current density across the seed layer on the substrate 48 is substantially uniform. If the answer to decision step 411 is "YES", then the process 400 continues to step 412.

In step 412, method 400 continues the electroplating process as long as desired. Since the electric current density across the seed layer on the substrate is substantially uniform as per the above loop of steps 406 to 411, metal being deposited on the seed layer should be deposited at a substantially uniform rate over the plating face of the substrate. Method 400 then continues to step 414 in which the substrate 48 is removed from the electroplating cell 200.

Following step 414, method 400 continues to decision step 416 in which the controller 254 determines whether there are any other subsequent substrates to process. If the answer to decision step 416 is yes, then the process 400 loops back to step 402 to perform an identical operation the next selected sequential substrate, until there are no further selected substrates. If the answer to decision step 416 is no, then process 400 terminates. Method 400 may also be repeated or reaccessed using similar loops (for example once a minute) in case further substrates are to be processed by the electroplating cell 200. Though, after the loop of steps 406 to 411 has been performed once, the level of the electric current to be applied to subsequent similar substrates should remain similar. Thus, the methods shown in FIGs. 3 and 4 provide for deposition of very uniform deposition layers that is highly repeatable between subsequent substrates.

Although various embodiments that incorporate the teachings of the present invention have been shown and described in detail herein, those skilled in the art can readily devise many other varied embodiments that still incorporate these teachings.

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